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Momentum-dominated methane jet flame at sub-atmospheric pressure

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Abstract

The influence of pressure and flow rate on momentum-dominated methane laminar flames' flickering and radiation characteristics were experimental studied to provide a focused description of diffusion flame behavior at sub-atmospheric pressure of 50-100 kPa. Measurement system consisted of CCD camera, high speed camera and schlieren system, radiation flux meter. Parameters including flame length, liftoff height, flickering frequency, and radiation intensity were compared and analyzed over the pressure range of 50-100 kPa in a low pressure combustion cabin. The controlled fuel mass flow rates provided diffusion flames of 5.95-23.81 mg/s stable at all ambient pressures considered. Experiment results indicated that for momentum-dominated jet flame, flame lengths were not dependent on pressure but linearly dependent on mass flow rate. As soot volume fraction was strongly influenced by pressure, when pressure descended, the radiation intensity declined resulted from reduction of soot formation. Lift off phenomenon of diffusion flames was not significant, however, liftoff heights also increased with increasing pressure and mass flow rate gradually. A semi-quantitative explanation on combined effect of pressure and velocity on flickering frequency was given as $f = 0.227u^{0.18}P_{\infty}^{1/3}$. All experiment data was in good agreement with theoretical analysis.

Keywords: Momentum-dominated diffusion flame; Sub-atmospheric pressure; Flickering frequency; Radiation; Flame length

Nomenclature

d	burner diameter (m)
D	diffusion coefficient (m^2/s)
f	flame flickering frequency (Hz)
Fr	Froude number
g	gravitational acceleration (kg/m^2)
H_l	flame liftoff height (m)
L	flame mean beam length (m)
L_f	flame length (m)
$\dot{m}$	mass flow rate (g/s)
$\overline{m}'''$	soot formation per unit volume (g/m^3)
P_{∞}	ambient pressure (kPa)
$\dot{q}''_{rad}$	flame radiation (W/m^2)
Re	Reynolds number
T_f	flame temperature (K)
u	fuel exit velocity (m/s)
V	volume flow rate (lpm: L/min; m^3/s)

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Greek symbols	
ρ_g	gas density of fuel (kg/m^3)
ρ_∞	gas density of ambient air (kg/m^3)
σ	Stefan–Boltzmann constant (W/m^2 K^4)
κ_g , κ_s , κ_m	absorption-emission coefficient of gas, soot and mixture

1. Introduction

Influence of pressure on combustion has been widely investigated and discussed from different aspects such as flame appearance, flickering characteristics, temperature field, soot formation mechanism and chemical reaction kinetics. Gaseous methane, as a typical gas of broad use, was both experimental and numerical studied in previous studies. Most et al. [1] experimentally studied the effects of gravity and pressure on diffusion flame's height, radiation fraction and temperature. It was found that radiation intensity grew when pressure increased. Gülder et al. [2-4] conducted a serious of experimental and numerical research work on characteristic flames at high ambient pressure (1-60 atm). They suggested that the height of buoyancy-dominated laminar co-flow diffusion flames scaled with fuel volume flow rate and diffusion coefficient, $L_f \propto VD^{-1}$. Durox et al. [5] pointed out that the flickering frequency of jet flame had a dependence on a third power of pressure. Miller and Maahs [6] indicated that soot volume fraction increased with $P_\infty^{\ 3}$. And O. V. Roditcheva and Bai [7] found that soot yield of turbulent flames was mostly sensitive to the soot surface growth rate and pressure increase by applying a semi-empirical model. Recently Timothy Ombrello et al. [8] proposed a Hencken burner to produce a steady, laminar and near one-dimension flame for detailed flame studies at 16.7 kPa and 100 kPa. Experiment data showed that for diffusion flame, the flame liftoff height was nearly linearly proportional to fuel exit flow velocity. By now, most of work on jet flame versus pressure was conducted in relatively small combustion and the radiation feedback and air flow convection may influence the result and the mainly flame type was buoyancy-dominated type. Hence, the impetus for this study was to experimental study on pressure and flow rate impact on momentum-dominated methane laminar diffusion flames at 50-100 kPa in a relatively larger confined low air pressure cabin (12 m^3). By measuring flow rate, flame length, liftoff height, flickering frequency and radiation flux, image and radiation characteristics was analyzed, The relations among pressure, mass flow rate, fuel flow velocity and parameters mentioned above were discussed. A semi-quantitative explanation on the combined effect of pressure and velocity on flickering frequency was given, which was in good agreement with experimental data.

2. Experimental setup

Low air pressure ambient was made within a confined cabin (Fig. 1(a)), the inside size of which was 3 m × 2 m × 2 m. The design pressure range was from 40 kPa to 100 kPa using a vacuum air pump. The experimental setup consisted of three parts as shown in Fig. 1, a round burner and a gas mass flow rate controller to make stable flames, a high speed camera and a schlieren measurement system to capture the flame's images and gas flow field, and a radiation heat flux meter to measure the radiation intensity of the flame.

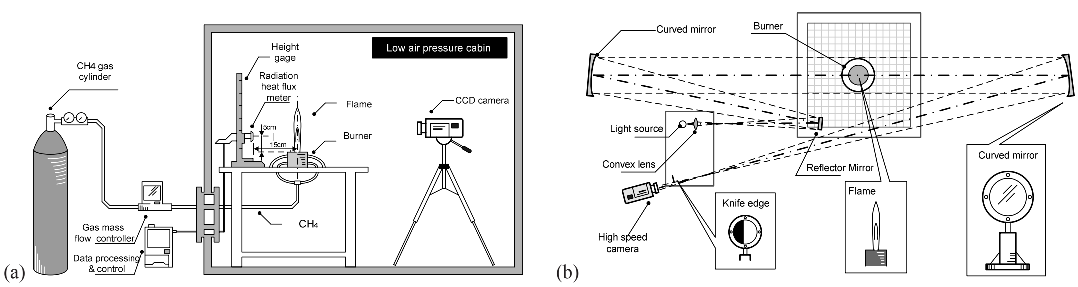


Fig. 1. (a) Scheme of experiment setup. (b) scheme of high-speed schlieren measurement system.

The fuel burner has an exit diameter of 3 mm. Gaseous methane (CH_4 with 99.99% purity) was supplied from the compressed gas cylinders measured by a calibrated mass flow meter with 0.2% full scale accuracy. The flames were ignited with a set of high voltage ignition system that was retracted from the burner once the flame was stable. Monitoring measurements included the fuel mass flow rate, the ambient pressure, ambient temperature and humidity. Four cases of methane flow rates under three different air pressure conditions were investigated to study the influence of pressure on methane diffusion flames. During each set of the experiments, the methane mass rate of 23.81, 17.86, 11.90, 5.96 mg/s (also could be expressed with 2.0, 1.5, 1.0, 0.5 slpm (standard liters per minute)) and the ambient temperature and humidity of 285 ± 1 K and 60 ± 5% were kept constant under all air pressures. Table 1 shows the physical parameters of fuel streams for experiments.

Table 1. Summary of experiment conditions

P_∞ (kPa)	$\dot{m}$ (10^{-3} g/s)	V lpm (L/min)	V (m^3/s)	u (m/s)	Fr	Re
50	5.95	1.00	1.67E-05	2.36	189	239
	11.90	2.00	3.33E-05	4.72	756	477
	17.86	3.00	5.00E-05	7.07	1702	716
	23.81	4.00	6.67E-05	9.43	3026	955
60	5.95	0.83	1.39E-05	1.96	131	239
	11.90	1.67	2.78E-05	3.93	525	477
	17.86	2.50	4.17E-05	5.89	1182	716
	23.81	3.33	5.56E-05	7.86	2101	955
70	5.95	0.71	1.19E-05	1.68	96	239
	11.90	1.43	2.38E-05	3.37	386	477
	17.86	2.14	3.57E-05	5.05	868	716
	23.81	2.86	4.76E-05	6.74	1544	955
80	5.95	0.63	1.04E-05	1.47	74	239
	11.90	1.25	2.08E-05	2.95	295	477
	17.86	1.88	3.13E-05	4.42	665	716
	23.81	2.50	4.17E-05	5.89	1182	955
90	5.95	0.56	9.26E-06	1.31	58	239
	11.90	1.11	1.85E-05	2.62	233	477
	17.86	1.67	2.78E-05	3.93	525	716
	23.81	2.22	3.70E-05	5.24	934	955
100	5.95	0.50	8.33E-06	1.18	47	239
	11.90	1.00	1.67E-05	2.36	189	477
	17.86	1.50	2.50E-05	3.54	425	716
	23.81	2.00	3.33E-05	4.72	756	955

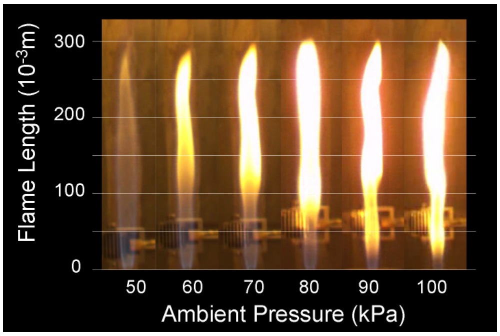


Fig. 2. The CCD photographs of the present round methane laminar diffusion jet flames of 23.81 mg/s at various pressures of 50/60/70/80/90/100 kPa.

The fuel jet exit velocities are in a range between 1.18 and 9.43 m/s with the Reynolds number (Re No.) of 239-955 and Froude number (*Fr* No.) of 47-3026. And according to Ref. [9], the flame type measured here was momentum-dominated laminar jet flame.

The luminous flame length and structure information were obtained using a 720 p Hitachi CCD camera at a framing rate of 30 fps and image processing computer. To record the full details of the flickering frequency of the flames, a high-speed camera with full resolution of 1024 × 1024 at frame rates of 250 fps (flames per second) with a camera shutter speed of 1/1000 s was used. Also a high-speed schlieren imaging system (Fig. 1(b)) utilizing the same flaming rate and 1/500 s shutter speed was applied to capture the evolution of hot gases and their interaction with ambient air. The radiative heat flux was measured using a calibrated Medtherm radiometer positioned 15 cm form the center of the burner and a height of 5 cm above the burner (Fig. 1(a)). The precision of radiant heat flux sensor was 1.5 W/m^2.

3. **Results and discussion**

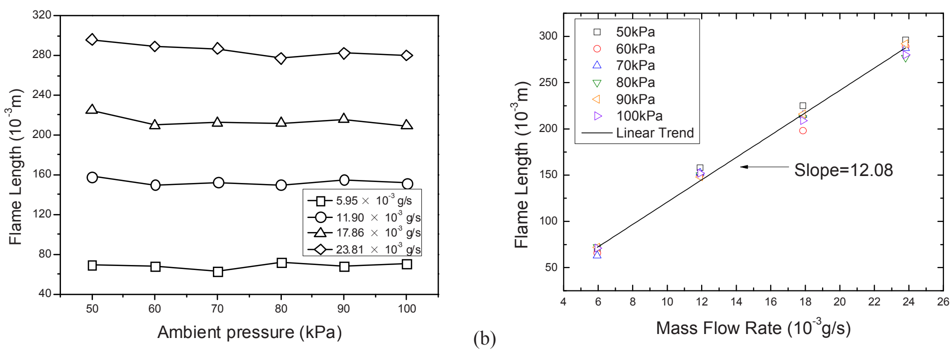
3.1. Physical appearances of the flames

Figure 2 is the CCD images of methane diffusion flame of 23.81 mg/s under different pressures. The visible flame lengths were all about 300 ± 5 mm. It was shown that the flame bottom is blue burnt gas regime, and its color is decided by the radiation of C2 and CH. As the axial distance from the burner surface grew, the flame turned to be more yellow, which indicated that it reached soot radiation dominant zone [10]. All experiment result showed that when ambient air pressure increased, the yellow area of methane diffusion flame increased and the flame turned to be brighter due to luminosity from hot primary soot particles; small eddy structures appeared, and the flames seemed to become turbulent. This result was probably due to the positive effect of pressure on soot formation rate and radiant heat transfer, which will be presented in the following.

3.2. Flame length

The lengths of diffusion flames have been widely studied experimentally and theoretically. Flame lengths are typically defined in terms of the mean temperature, chemical composition or luminosity along the axis. Since the flickering characteristics, flame lengths were difficult to directly observed and determined. A digital image method [11] was introduced to process the flame images taken from CCD. The flame contour of 50% luminous frequency was used for analyzing flame lengths, radiuses and areas [12]. The flame lengths processed is shown in Fig. 3. It was found that flame length was almost independent of ambient pressure, but increased when mass flow rate grew (Fig. 3). As the test flame was momentum-dominated jet flame, the flame length could be expressed as [9]:

$$L_f = \frac{V}{2\pi D} = \frac{\dot{m}}{2\pi \rho_g D} \tag{1}$$



(a) (b)

Fig. 3. (a) Plot of flame length of the relation of ambient pressure and flame length; (b) the relation of mass flow rate and flame length.

Since the gas density of fuel is proportional to pressure ($\rho \propto P_\infty$) whereas diffusion coefficient is inversely with pressure ($D \propto P_\infty^{-1}$), the momentum-dominated laminar jet flame's length of same mass flow rate (*Re* No.) is independent on ambient pressure. Hence, at all pressures presented, the flame length of methane diffusion flames remained the same. However, with different mass flow rates, the flame lengths changed. From Fig. 3(b), it was showed that there was a positive linearity relation between flame length and mass flow rate under the pressure condition presented:

$$L_f \propto 12.08\dot{m} \tag{2}$$

3.3. Flame liftoff height

Lift off is a special phenomenon of jet flame (Fig. 4(a)). It occurs when fuel exit flow velocity is larger than flame spread speed. The liftoff heights (location of flame bottom above the burner surface) as a function of ambient pressure were measured from the images of methane flames and are showed in Fig. 4(b).

The liftoff heights of all measured flow rate showed similar trend versus ambient pressure. When pressure increased, the liftoff height decreased; at the high mass flow rate (23.81/17.86 mg/s), there was nearly no lift off at 90-100 kPa. The possible explanation is that the flow velocity has strong effect on liftoff height. Ref [8] showed that when for flow velocity of methane- air of more than 55 cm/s, the liftoff height increased significantly versus flow velocity for the same mass flow rate. And apparently, for momentum-dominated laminar jet flames, methane diffusion flames also followed this trend ($u \propto P^{-1}$ at the same mass flow rate).

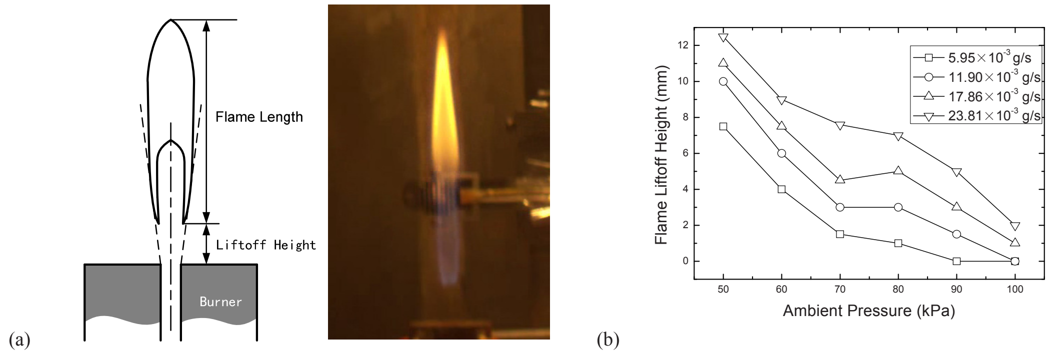


Fig. 4. (a) Scheme of lift off phenomenon; (b) plot of flame liftoff height versus ambient pressure for methane diffusion flames of 5.93/11.90/17.86/23.81 mg/s at 60/70/80/90/100 kPa.

3.4. Flickering frequency

A flame fluctuation characterized by low-frequency vertical oscillations ranging from 10 to 20 Hz is generally considered as a flickering flame. For flickering characteristics, Durox et al. [5] indicated that flickering frequency depended on the gravity and pressure for relatively small burners:

$$f \propto P_\infty^{1/3} g^{2/3} \tag{3}$$

H. Sato et al. [13] later studied flickering frequency of different flow velocities subject to various gravity fields, and suggested that for flickering flames whose Froude number was larger than 10, if the burner diameter and gravity level were fixed, flickering frequency was only dependent on fuel flow velocity:

$$f \propto u^{0.18} \tag{4}$$

And Eq. (3) could be simplified if gravity level keeps constant to:

$$f \propto P_\infty^{1/3} \tag{5}$$

To study the combined effect of pressure and velocity on flickering frequency, the flickering frequency spectra of methane diffusion flames were measured from FFT analysis of mean pixel intensity of the flame high-speed photographs

(Fig. 5) and also from the high-speed schlieren measurement system (Fig. 6). The results obtained from both measures were in a good agreement, and was presented in Fig. 7. In Fig. 8, the fitted plot suggests a relation:

$$f = 0.227u^{0.18}P_{\infty}^{1/3} \tag{6}$$

which means that the flickering frequency of momentum-dominated methane diffusion laminar jet flames tended to increases with increasing $u^{0.18}P_{\infty}^{1/3}$, and indicates the two factors' co-influence on flickering frequency.

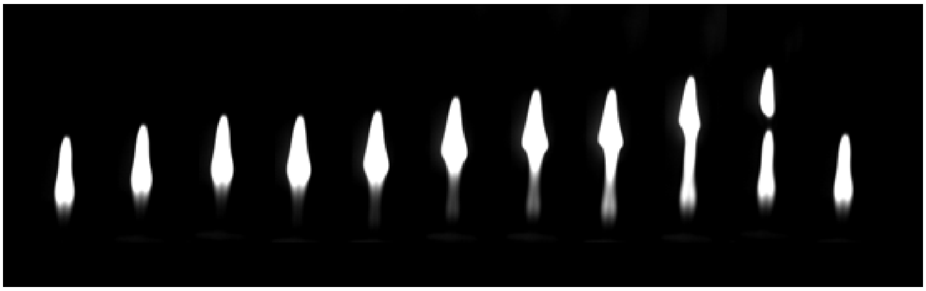


Fig. 5. A flickering cycle images of methane diffusion flame of 11.90 mg/s at 80 kPa.

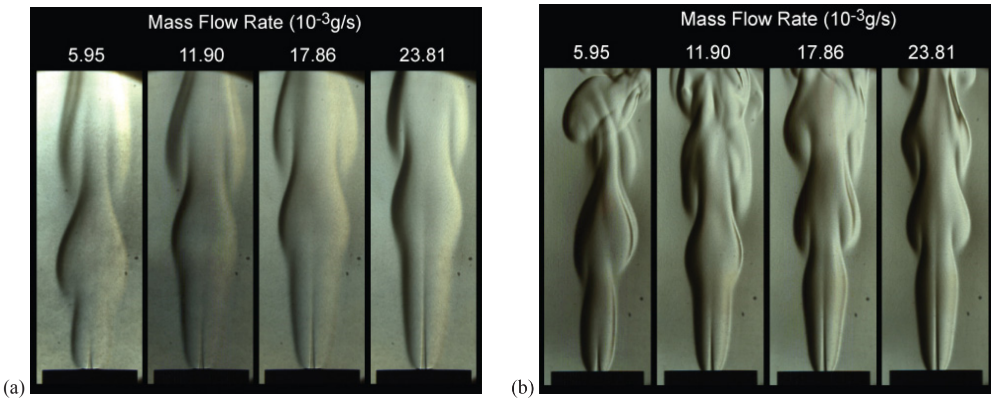


Fig. 6. (a) Schlieren photographs of methane diffusion flames of 5.95/11.90/17.86/23.81 mg/s at 70 kPa; (b) schlieren photographs of methane diffusion flames of 5.95/11.90/17.86/23.81 mg/s at 100 kPa.

3.5. Thermal radiation

The influence of soot on the flame comes mostly through radiative heat transfer. The influence of the radiation is included into the calculations by the consideration of different radiative parameters. The radiation heat flux of flame can be expressed as [14, 15]:

$$\dot{q}''_{rad} = \sigma T_f^4[1-\exp(-\kappa_m L)] \tag{7}$$

where $\kappa_m = \kappa_g + \kappa_s$ Soot absorption coefficient proportional to soot formation $\kappa_s \sim \overline{m}'''$, characteristic flame mean beam length $L \sim L_f$, and flame temperature T_f.

Soot formation decreased rapidly in low pressure as $\kappa_s \sim P_\infty^3$ [6]. As shown in Fig. 3 above, the upper yellow region of flame which showed the radiation emission of soot was shortening gradually with decreasing pressure. As the flame length is nearly independent of pressure, the radiation intensity should be weakened with decreasing pressure. Fig. 9 gives general pictures of flame radiation versus ambient pressure with different mass flow rates.

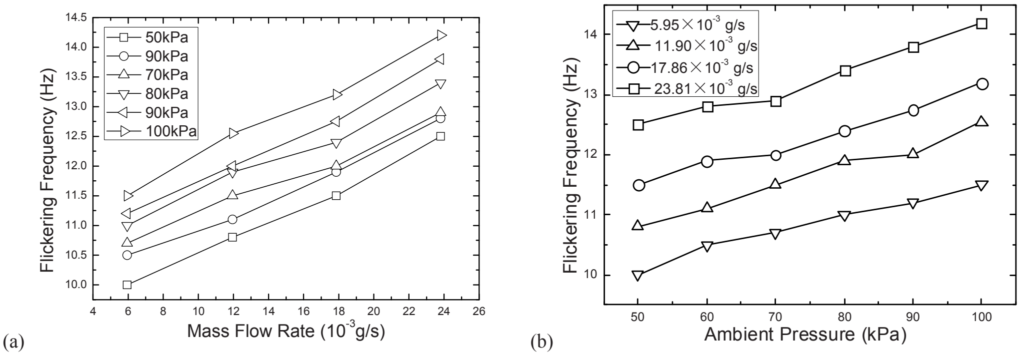


Fig. 7. (a) Plot of flickering frequency of methane diffusion flames *vs.* mass flow rate; (b) plot of flickering frequency of methane diffusion flames *vs.* ambient pressure.

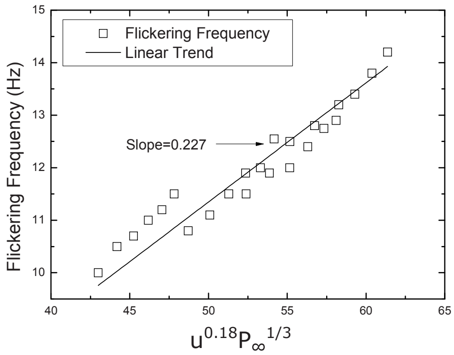


Fig. 8. Plot and fitted result of flickering frequency of methane diffusion flames *vs.* $u^{0.18}P_{\infty}^{1/3}$.

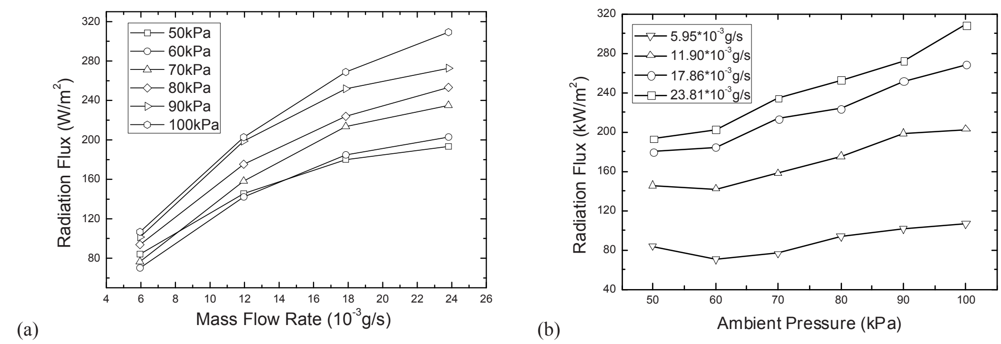


Fig. 9. (a) Plot of radiation flux versus mass flow rate at 50/60/70/80/90/100 kPa; (b) plot of radiation flux *vs.* ambient pressure of 5.95/11.90/17.86/23.81 mg/s.

4. Summary

Experimental data of momentum-dominated methane diffusion laminar jet flames of different mass flow rates at 50-100 kPa were analyzed to study the influence of pressure and flow rate on flames' flickering and radiation characteristics. A confined low pressure cabin was applied for measurement of mass flow rate, flames' lengths, lifted heights, flickering frequencies, radiation intensity. And semi-quantitative analysis was made for explain the flame behavior at sub-atmospheric pressures. All experiment data had a good agreement with theoretical analysis. From the result it may be concluded:

- Visible flame lengths was not affected by the change of pressure, but was positive proportional to mass flow rate. The linear relation between them was $L_f \infty 12.08\,\dot{m}$.
- Flame flickering frequency depended on both of burner exit velocity and pressure: $f = 0.227u^{0.18}P_{\infty}^{1/3}$.

• Flame radiation intensity was mainly rely on soot formation, which increased by an exponent of three with pressure [6].

In conclusion, pressure and flow rate both can influence flames' flickering and radiation characteristics. More detailed measurements are warranted to fully characterize the flames in the future work. And more work will be carried out on theoretical and numerical analysis of momentum-dominated diffusion flames.

Acknowledgements

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